A Lidar Approach to Measure CO2 Concentrations from Space for the ASCENDS Mission

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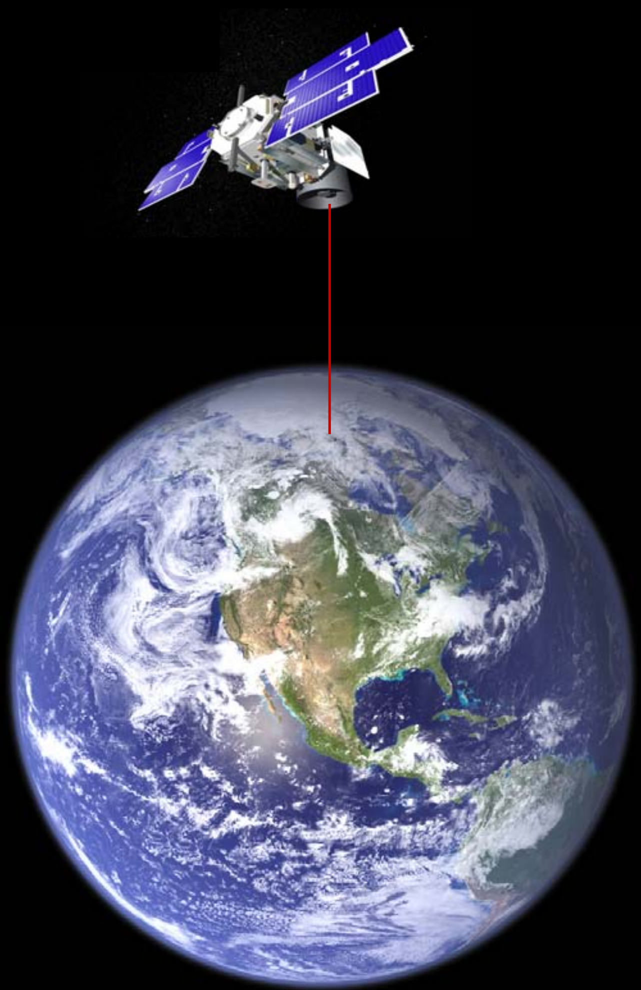

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SPIE Remote Sensing Europe

Paper 7832-11

September 21, 2010

Supported by:

NASA ESTO IIP , Goddard IRAD, ASCENDS Definition programs

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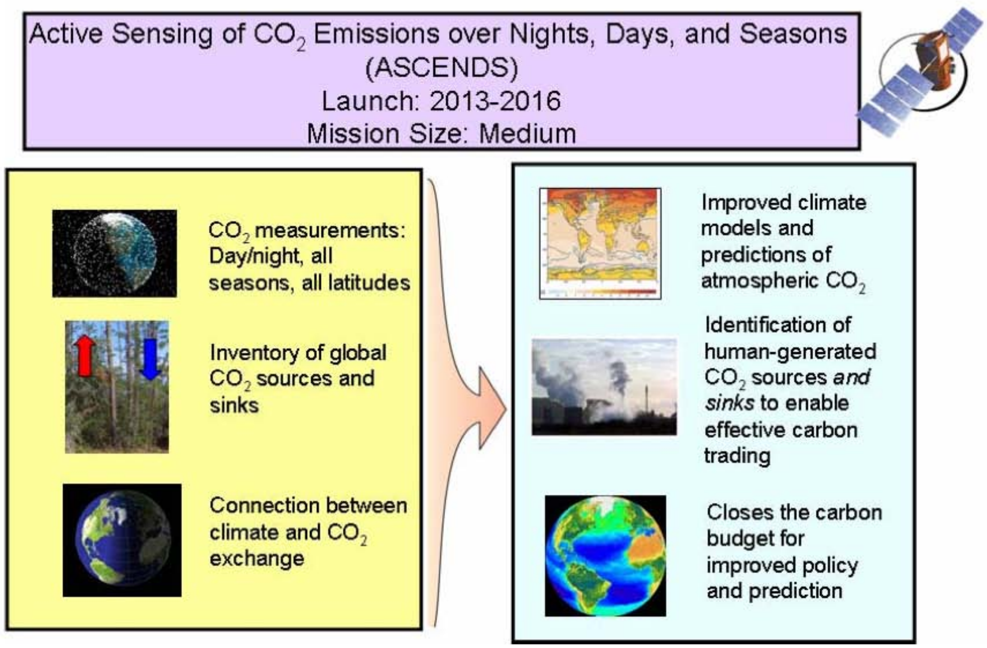
NASA's ASCENDS Mission

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)



Why lidar ?

- Measures at night & all times of day
- Measurements at high latitudes & continuous over oceans
- Constant nadir/zenith path
  - Illumination = observation path
- Measure through broken clouds & to cloud tops
- Very high spectral resolution and accuracy

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

NASA Science Definition and Planning Workshop Report

July 23-25, 2008
University of Michigan in Ann Arbor, Michigan

For more information, see
2008 Workshop report:
http://cce.nasa.gov/ascends/index.htm

Laser Sounder Approach for ASCENDS Mission

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Simultaneous laser measurements:

1. CO_2 lower tropospheric column

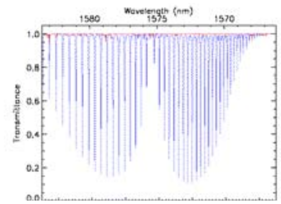
   One line near 1572 nm

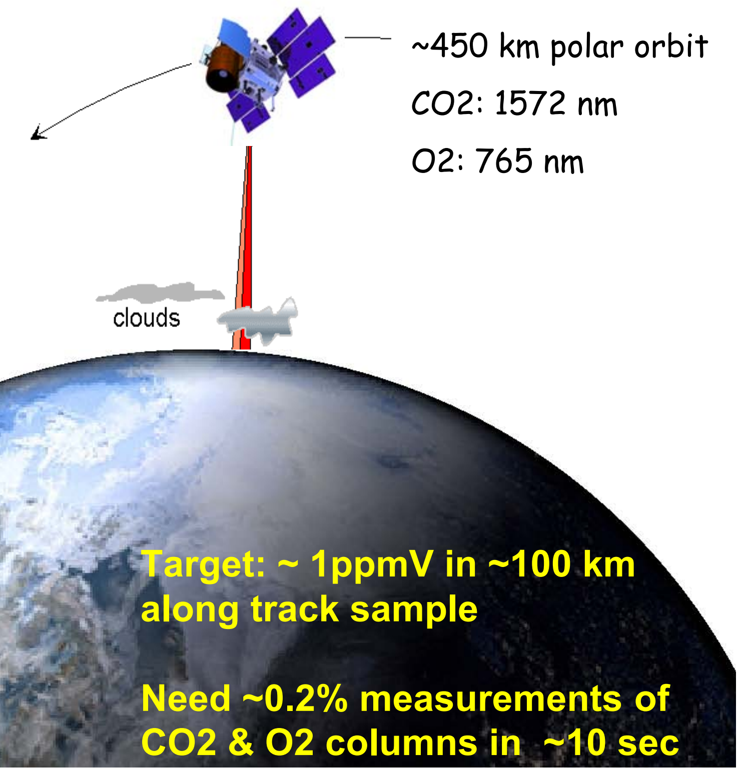
2. O_2 total column (surface pressure)

   Measure 2 lines near 765 nm

Altimetry & atmospheric backscatter profile from CO_2 signal:

Measures:
- CO_2 tropospheric column
- O_2 tropospheric column
- Cloud backscattering profile





Measurements use:

- Pulsed lasers
- ~10 KHZ pulse rates
- 8 laser wavelengths for CO_2 line
- Time resolved Photon counting receiver

CO_2 & O_2 column measurements:

- Pulsed signal approach :
  - Isolate full column signal from surface
  - Reduces noise from detector & solar background
  - Time of flight provides column length

CO2 Band, Line Sampling & Vertical Weighting Functions

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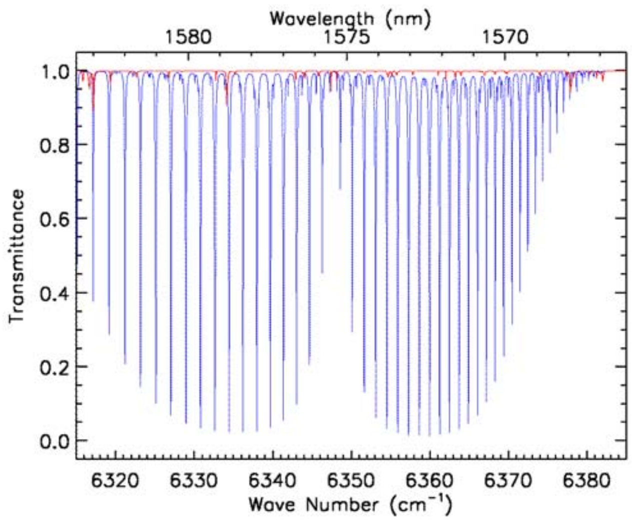
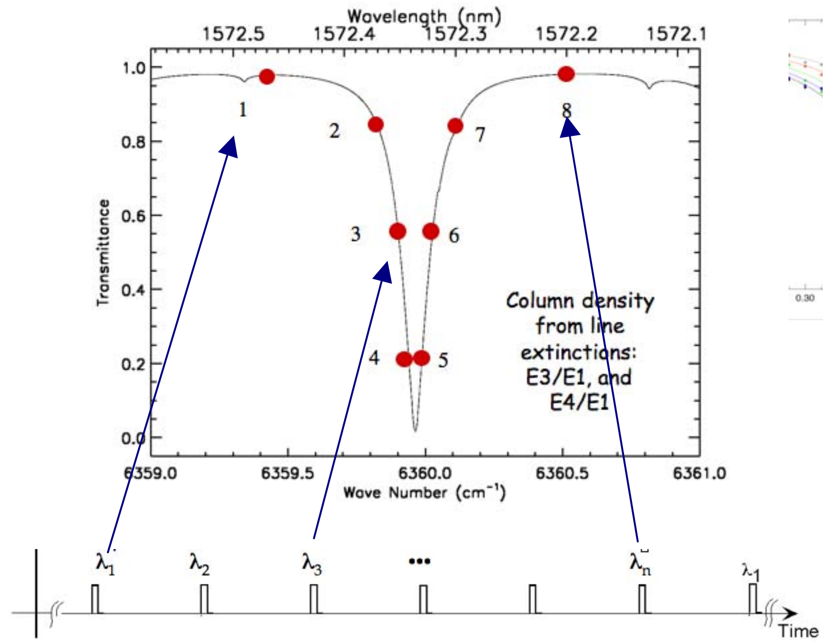
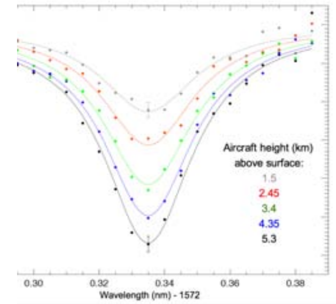
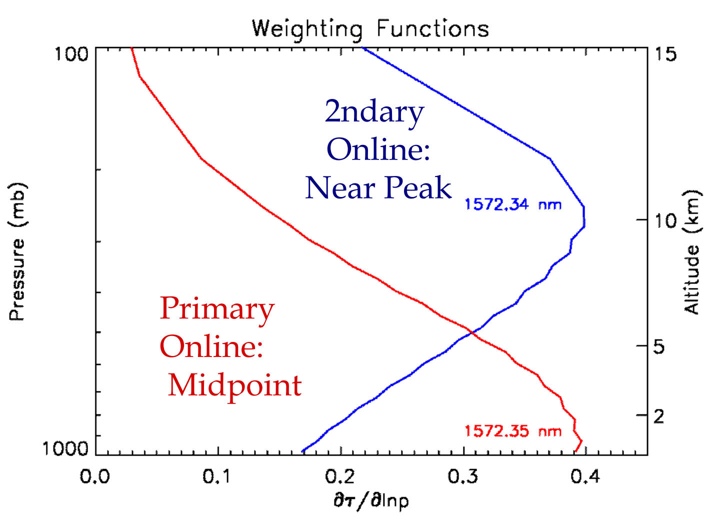






Increasing CO2 Column Density



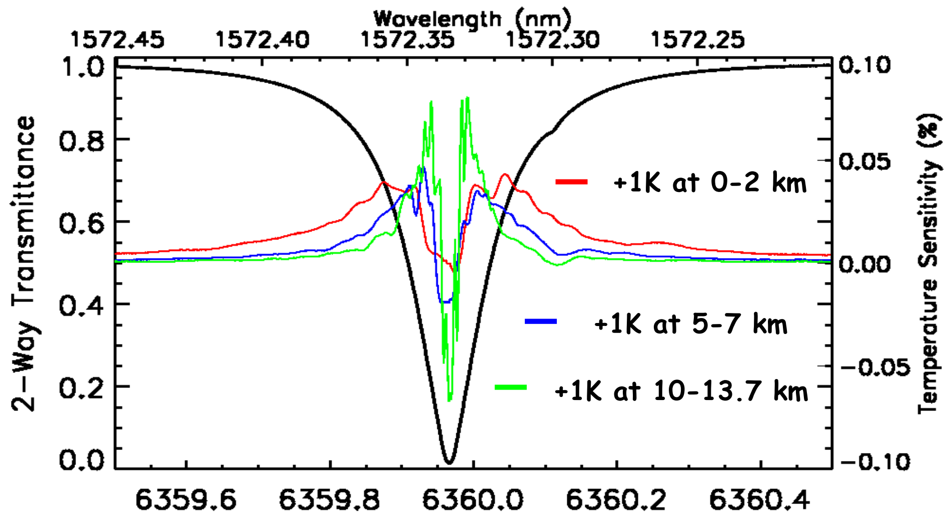
Total Column from area of line

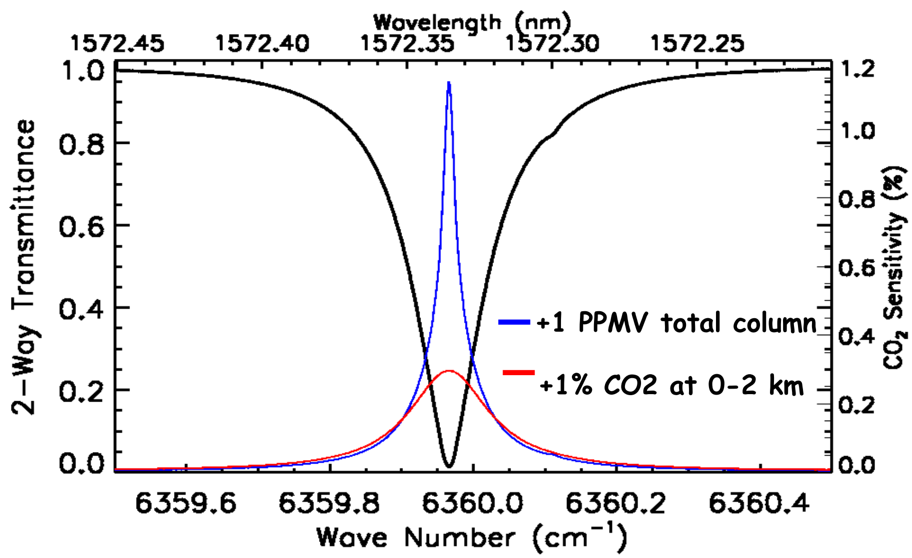
Space lidar: 8 wavelength samples across line

Multi-wavelength Line Sampling allows:

- Detection & correction of Doppler & λ errors
- Modeling & reducing errors from varying λ response
- CO2 retrievals for lower & upper troposphere
- Line shape information

1572.33 nm line is well suited for measurement



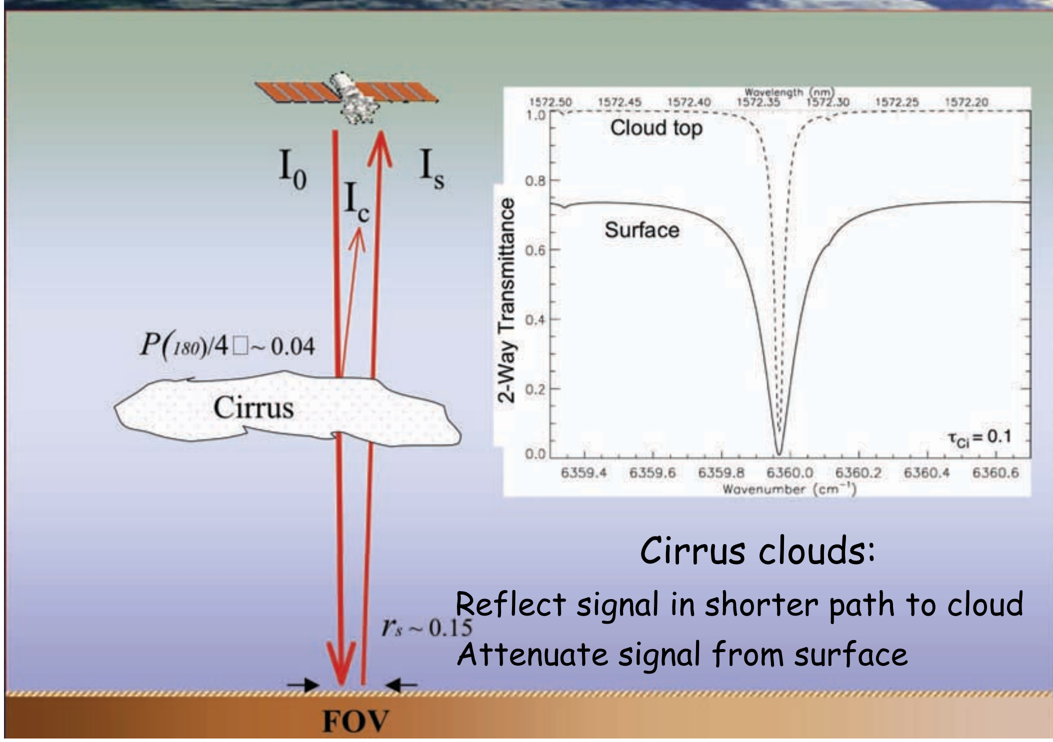


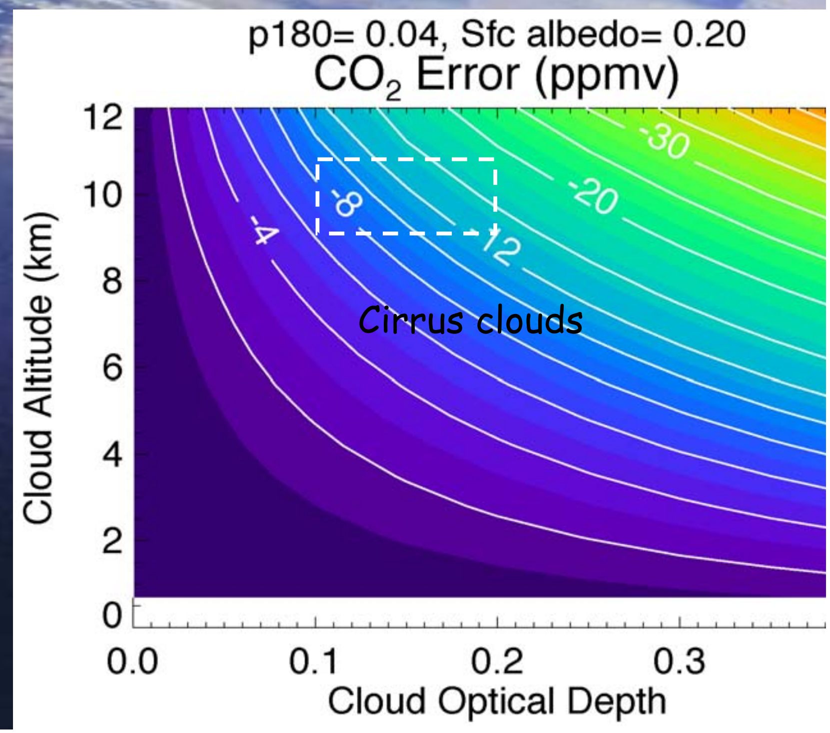
- ✓ Less sensitivity to atmospheric temperature
- ✓ Greater sensitivity to atmospheric CO2 amount

Why use pulsed lasers & range resolution ?

Atmospheric Scattering

- **Thin cirrus clouds are quite prevalent, β_π varies with λ**
- **Cloud reflections shorten average optical path -> bias non-gated column estimates**
- **Cirrus cloud scattering -> 4-10 ppm errors in non-range gated measurements**
- **Pulsed lasers & range gating eliminate these errors**

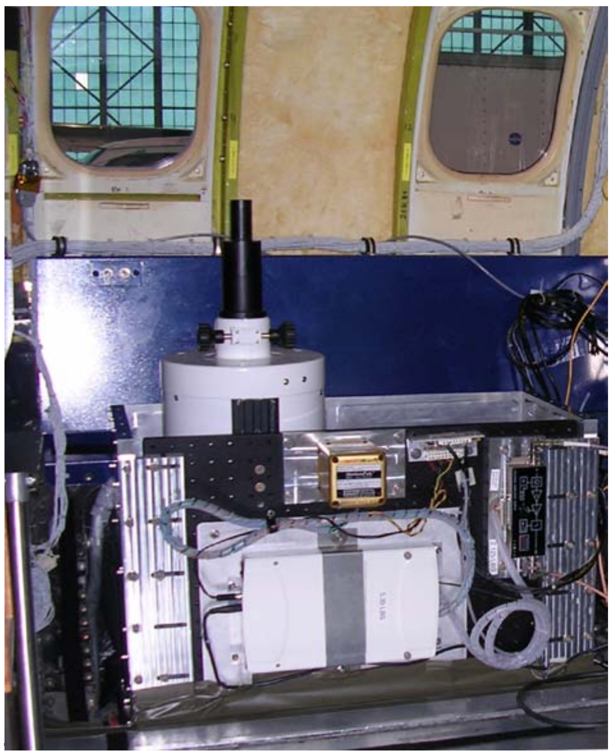


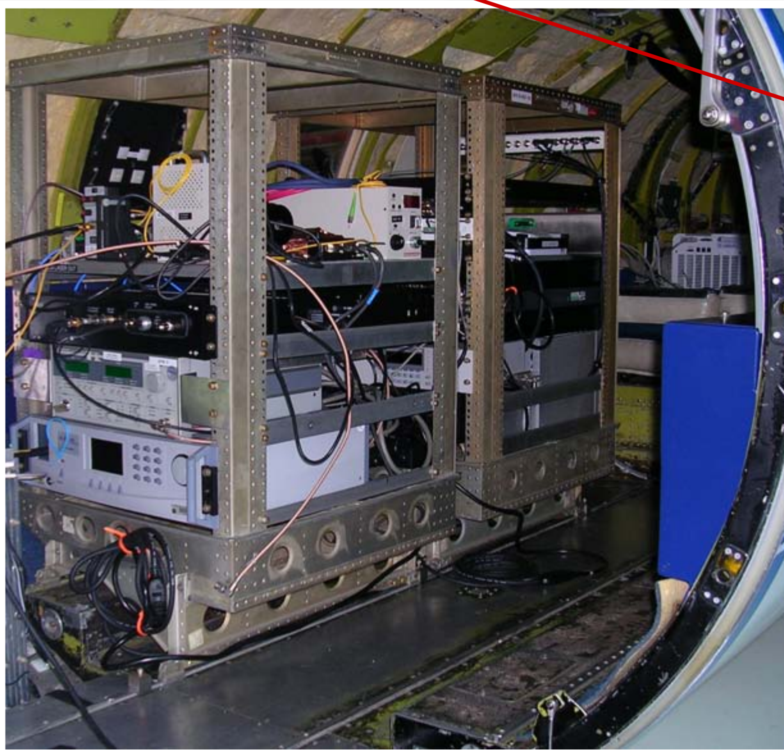


Pulsed Airborne CO2 Sounder Lidar on the NASA Glenn Lear-25

Experiment Team in Ponca City OK, USA

Nadir port showing transmit and receiver windows





Flights on Lear 25:

Oct & Dec 2008

July & August 2009

Pulsed Airborne CO2 Lidar

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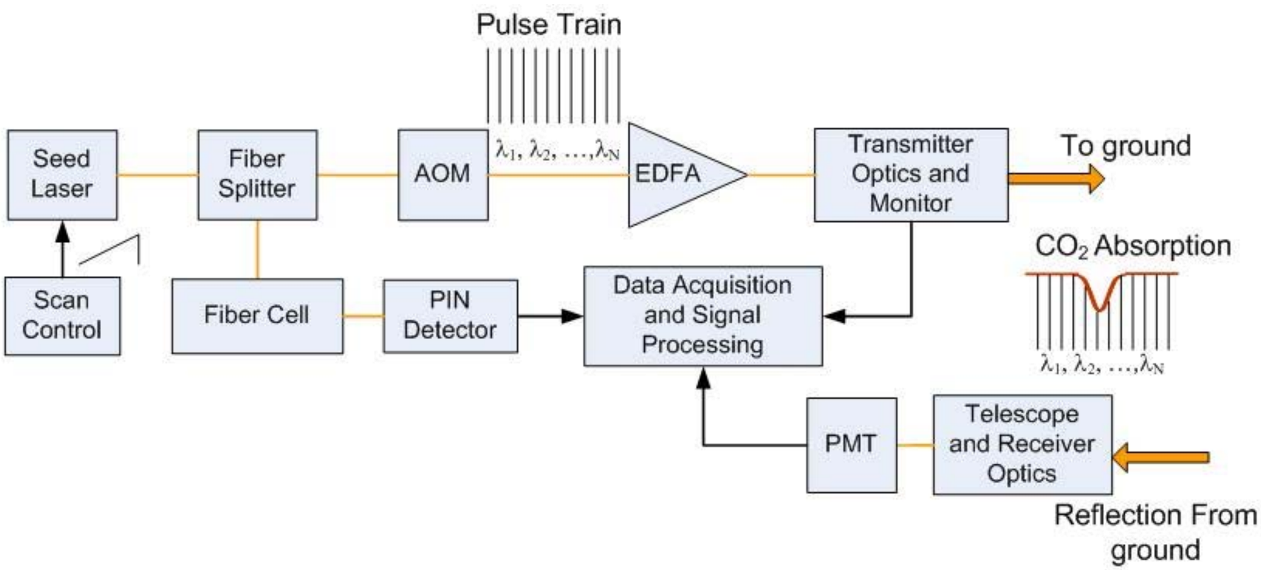

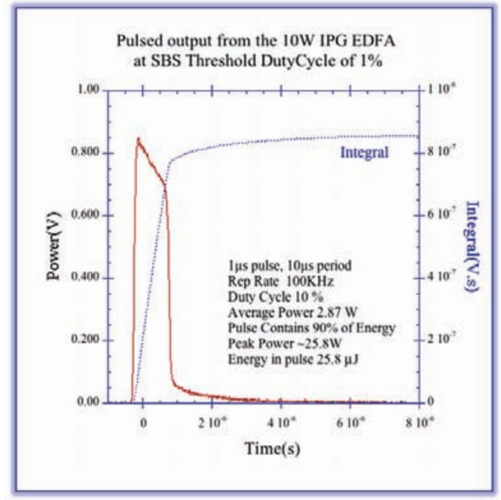

2009 Parameters:

Laser peak power: 24 watts (24 uJ/pulse)	Laser divergence angle: 100 urad
Laser: DFB diode laser, AOM, Fiber amplifier	CO2 line: 1572.33 nm
Wavelength scans: 20 wavelengths, 450 Hz	Receiver FOV: 200 urad
Telescope diameter: 20 cm	Receiver optical bandwidth: 0.8 nm
Receiver transmission: 65%*	Detector quantum efficiency: 2 %
PMT dark count rate: ~ 550 kHz	Receiver range bin size: 8 nsec

Coordinated Airborne Experiments to Measure CO2 column densities to support ASCENDS Science Mission Definition

(August 2009)

Examples of Measurements through 2 Cloud layers (cloud, cloud, ground echo pulses)

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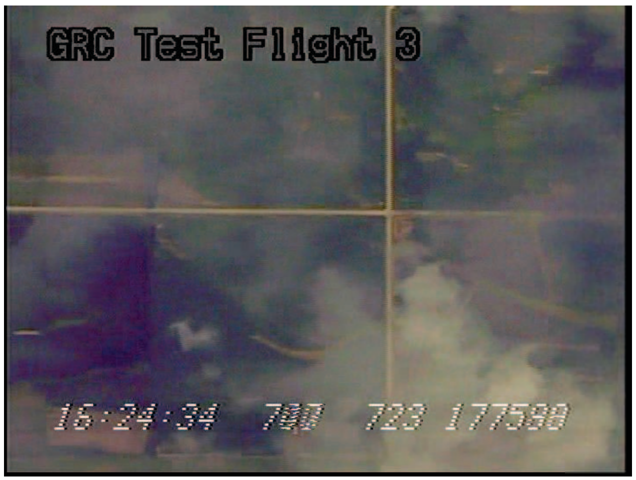
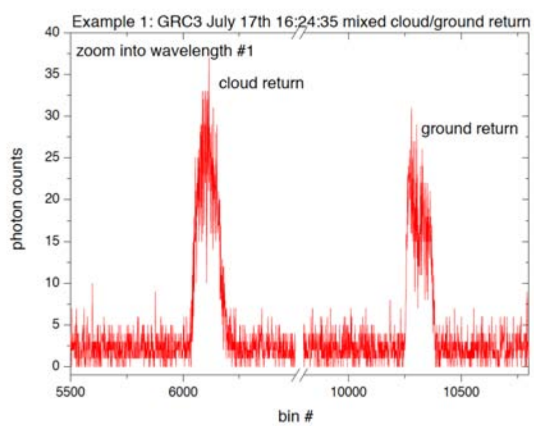
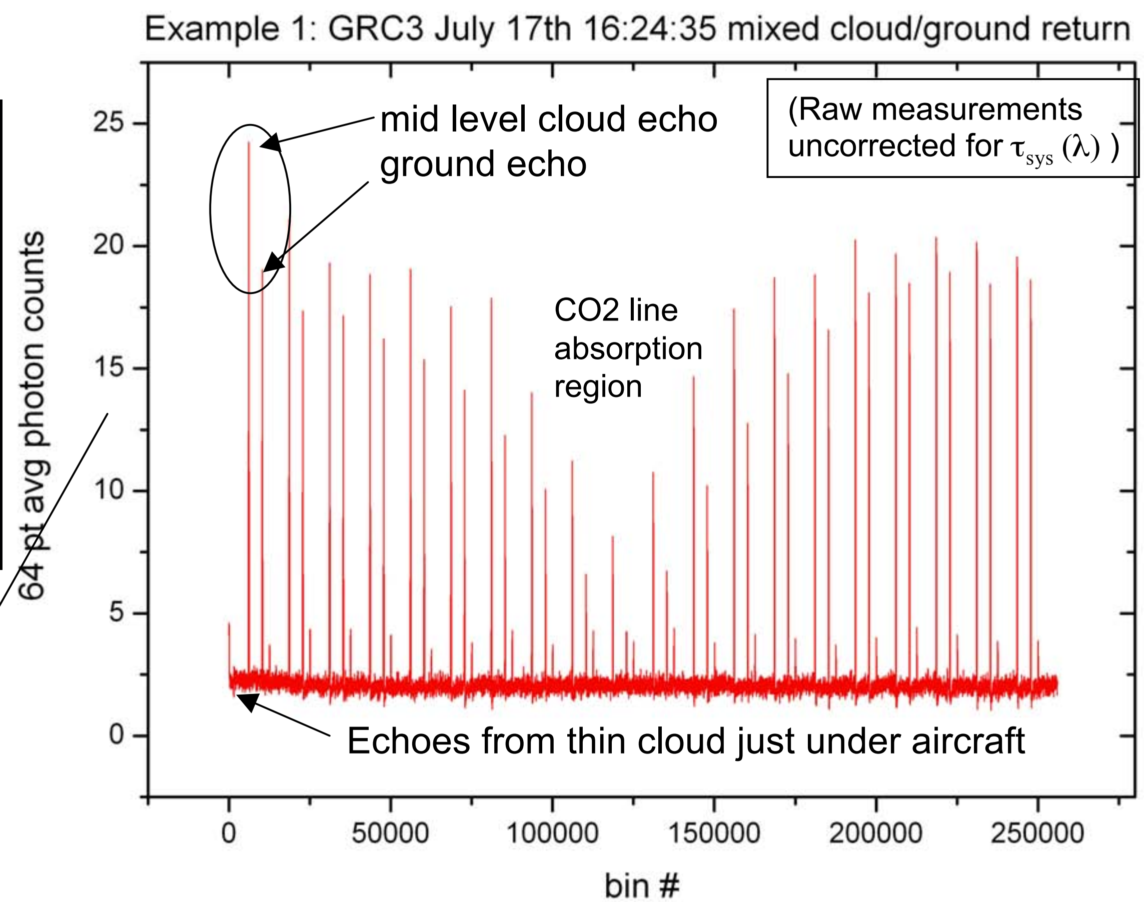
Nadir Camera Image for Measurement



Expanded view of 1st echo pulse group in sequence





Ranges & scattering Profiles from times of Flight of pulses

Absorption line shapes:
to clouds - thinner, less deep
to ground - broader & deeper

Examples of Line shapes vs Altitude
North Carolina Flight - August 17, 2009

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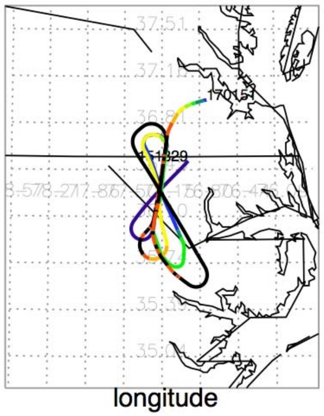

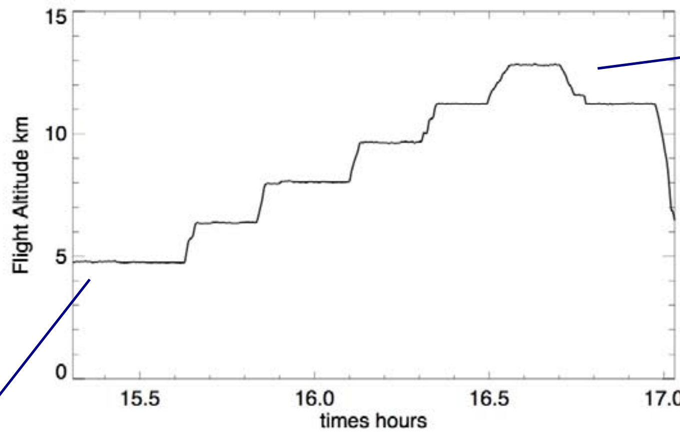

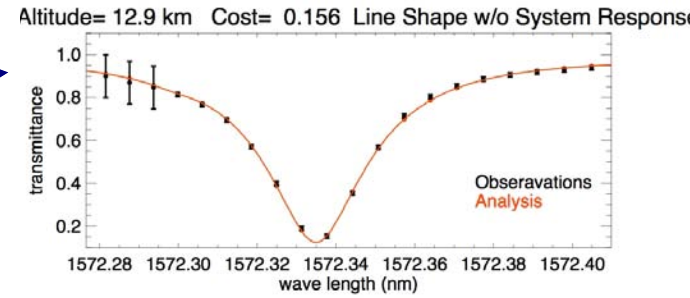

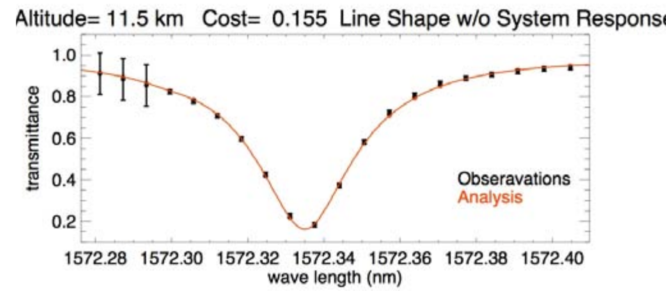

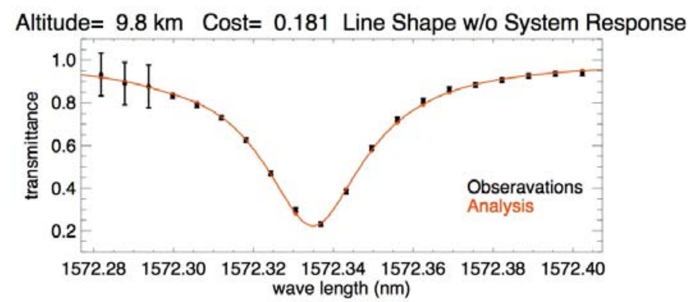

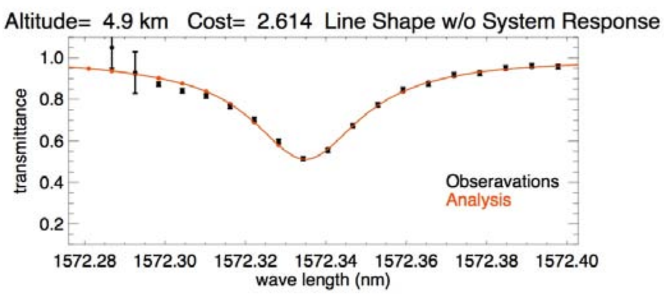

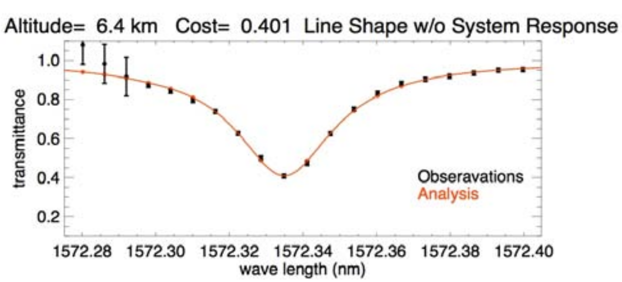

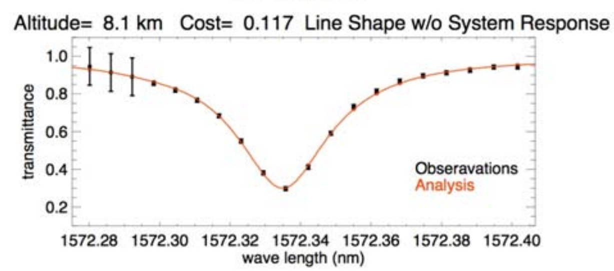

- Depth increases with altitude
- Smooth line shapes at all altitudes !

Line Optical Density & # Density vs Altitude
North Carolina Flight - August 17, 2009

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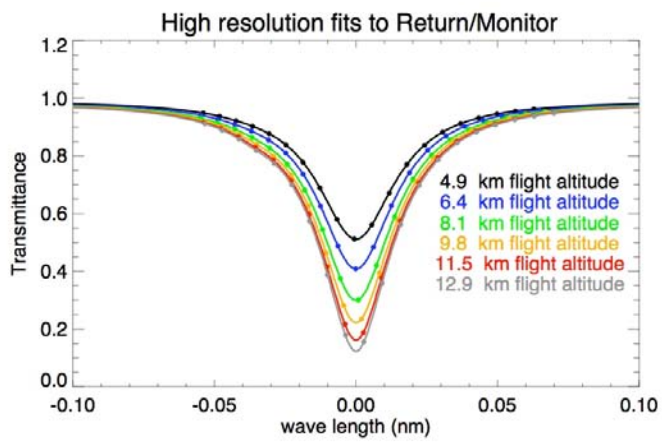

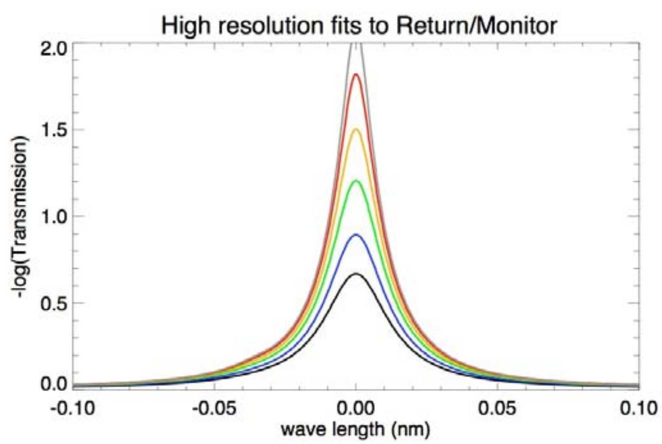

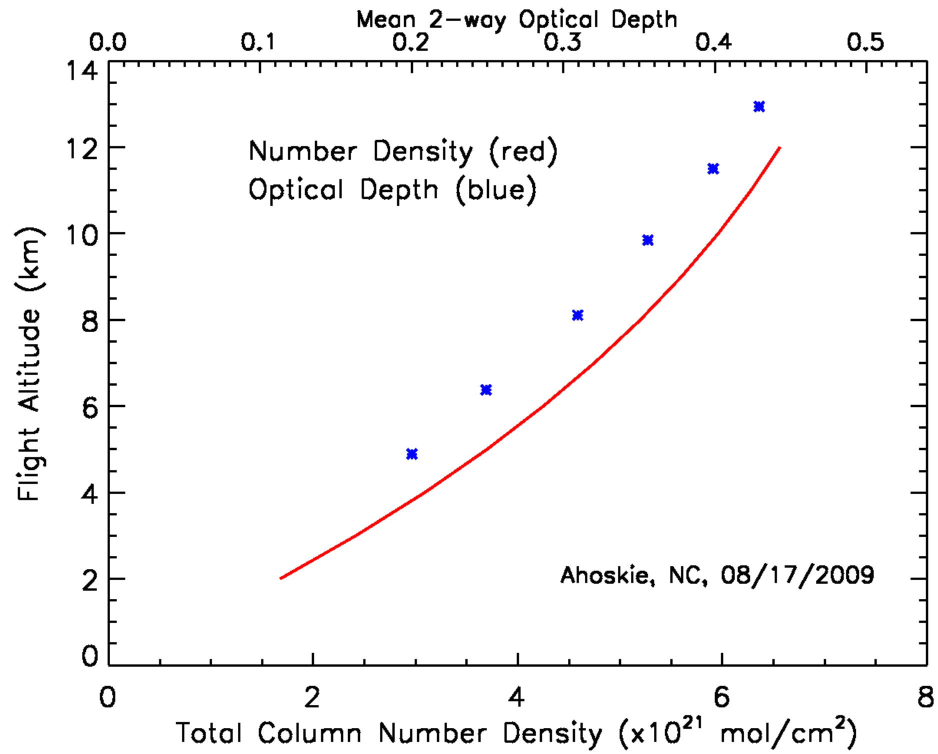

- Mean Optical Depths from line fits to CO2 Sounder measurements
- # Densities calculated from LaRC in-situ sensor and radiosonde readings

- 4 papers on 2009 CO2 & O2 measurements at 25th ILRC conference, St. Petersburg, Russia, July 2010.

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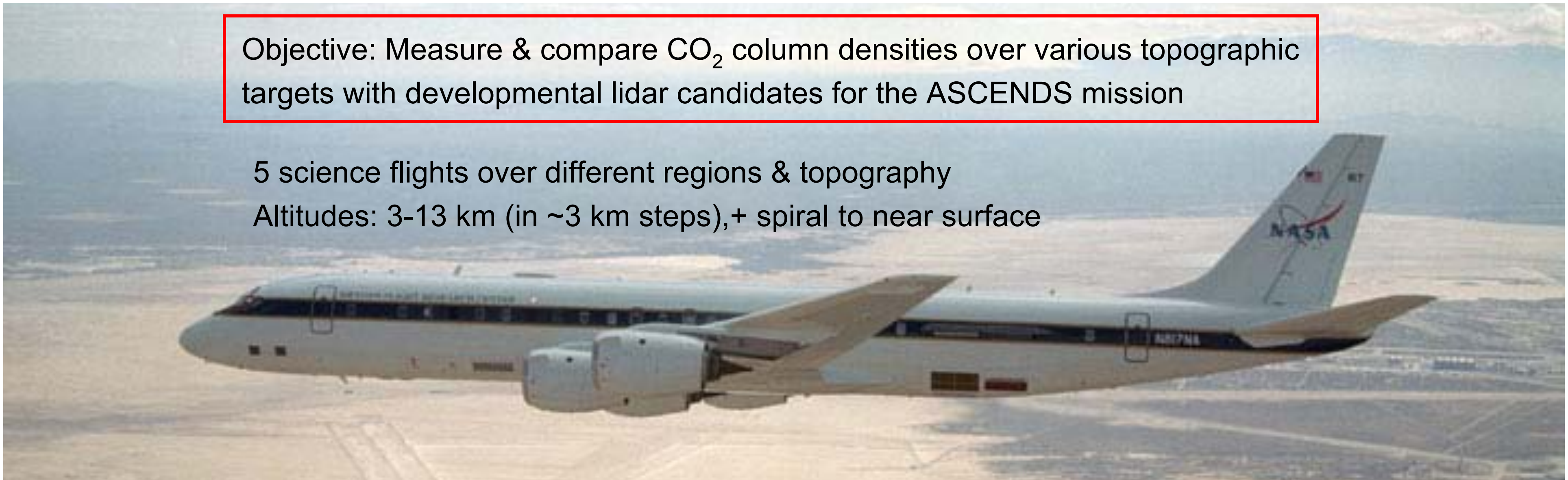
Airborne Experiments to Measure CO_2 Column Densities to Support ASCENDS Mission Definition; July 5-18, 2010

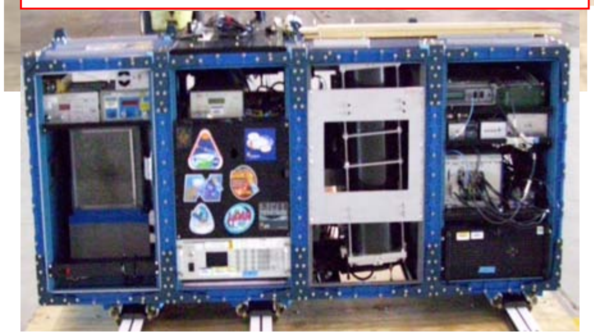


Objective: Measure & compare CO_2 column densities over various topographic targets with developmental lidar candidates for the ASCENDS mission

5 science flights over different regions & topography

Altitudes: 3-13 km (in ~3 km steps),+ spiral to near surface

LaRC/ITT instrument	GSFC instrument	JPL/LMCT instrument



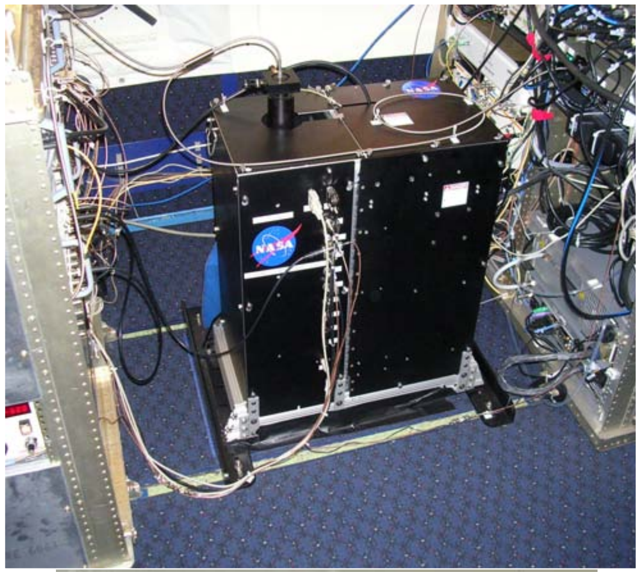
- Multi-functional Fiber Laser Lidar (MFLL)
- Ed Browell/LaRC, Team Leader
- Instrument development via ITT IRAD, NASA AITT funding, LaRC IRAD

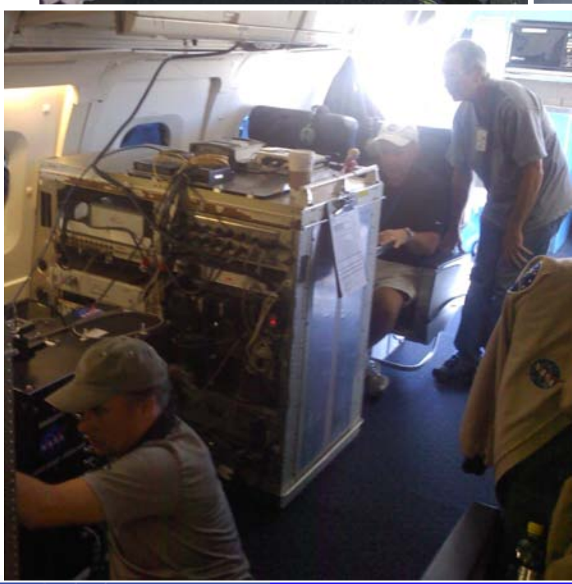
- CO_2 Sounder lidar with O_2 measurement experiment
- Jim Abshire/GSFC, Team Leader
- Instrument development via NASA ACT & IIP programs, GSFC IRAD

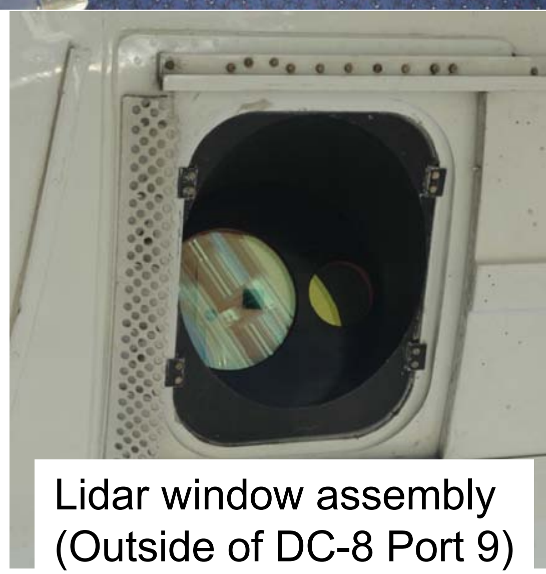
- CO_2 laser absorption spectrometer (CO_2LAS)
- Gary Spiers/JPL, Team Leader
- Instrument development via NASA ACT, IIP & AITT programs, JPL IRAD

ENDS Mission

CO2 Sounder: July 2010, NASA DC-8 configuration







Lidar window assembly
(Outside of DC-8 Port 9)

O2 absorption measurements from laboratory

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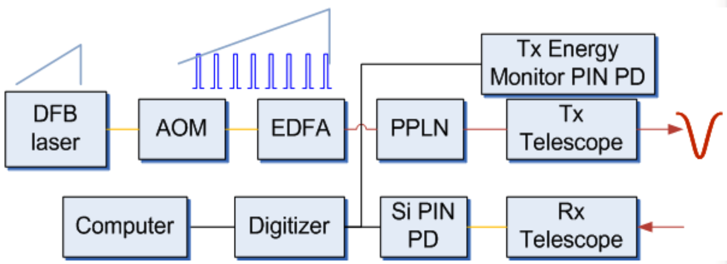
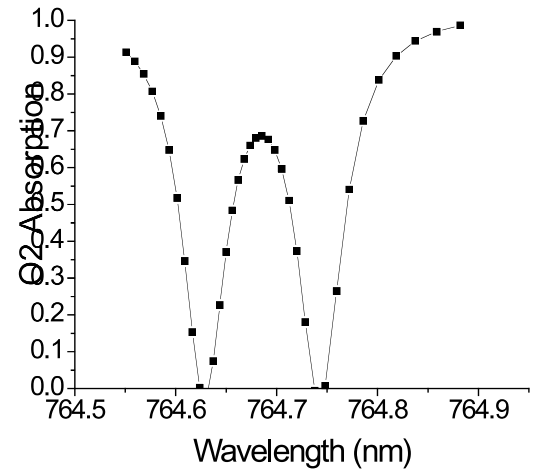




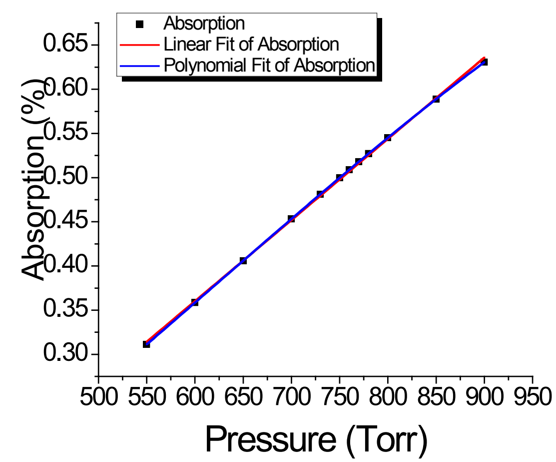
Airborne O2 Lidar Parameters:

- Diode laser Wavelength: 1529 nm
- Amplifier: NP Photonics EDFA
- Output Wavelength: 764.5 nm
- Output Energy: ~2 uJ/pulse
- Detector: Si APD SPCM
- Scan over the absorption with 40 Pulses (selectable) at 250 Hz

Distance to target: 1.5 km
Target illuminated by green alignment laser

B33 Room F411
"Truth:" Weather station on top of B33

Calculated



Initial Airborne lidar Measurements of O2 line & column absorption
Calculated O2 line shape vs altitude

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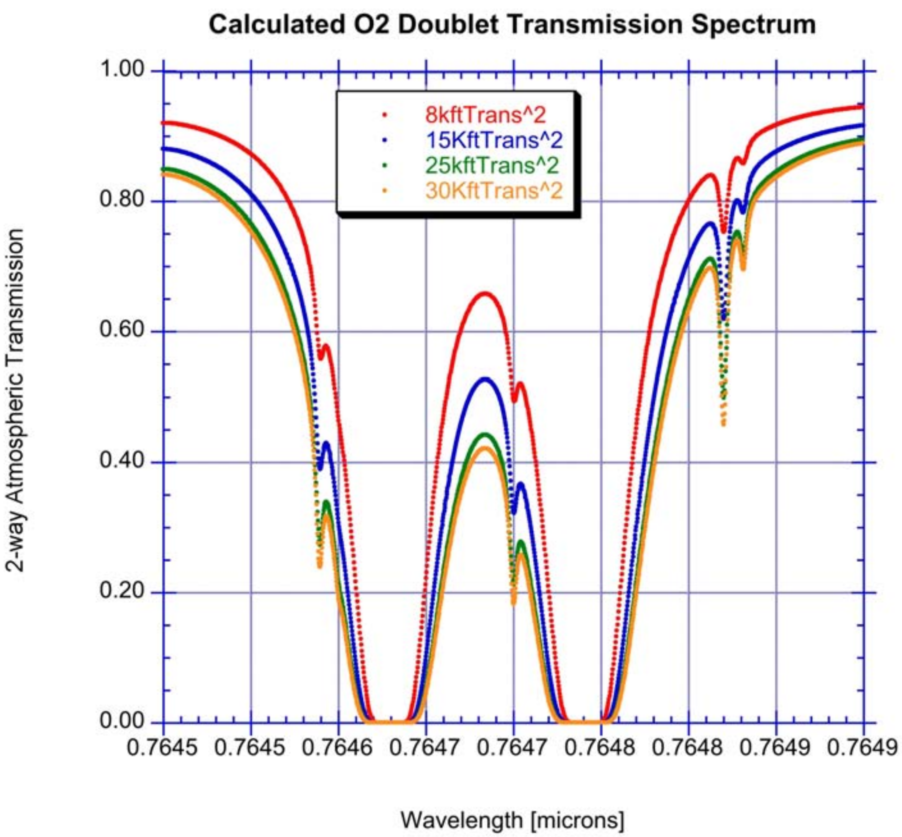
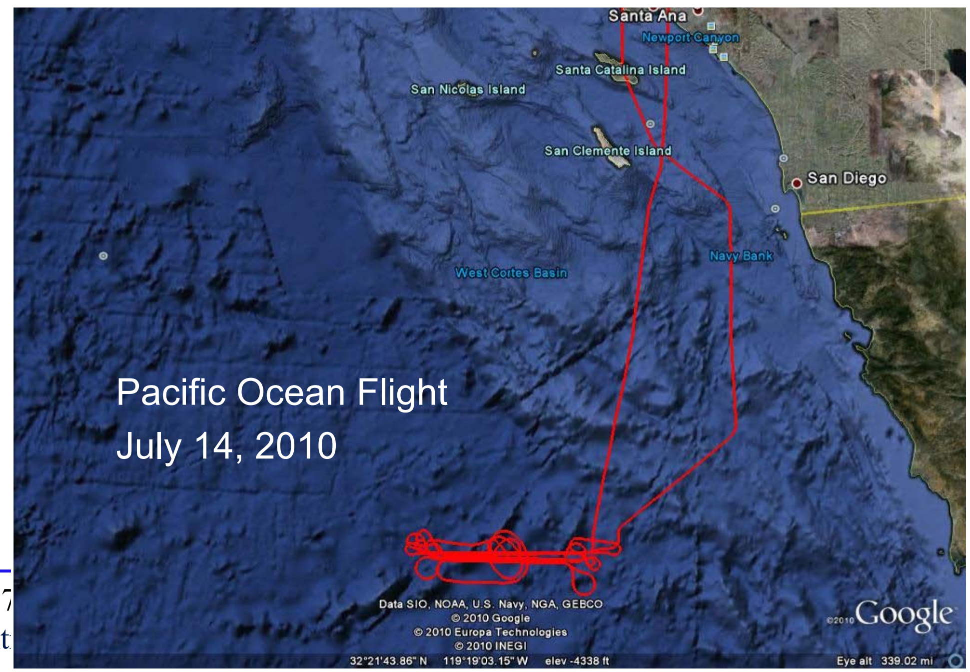


Bill Hasselbrack & Mike Rodriguez at CO2 (left) & O2 lidar (right) controls on NASA DC-8 during July 2010



Airborne lidar Measurement of O2 line column absorption made on July 14, 2010 over Pacific Ocean

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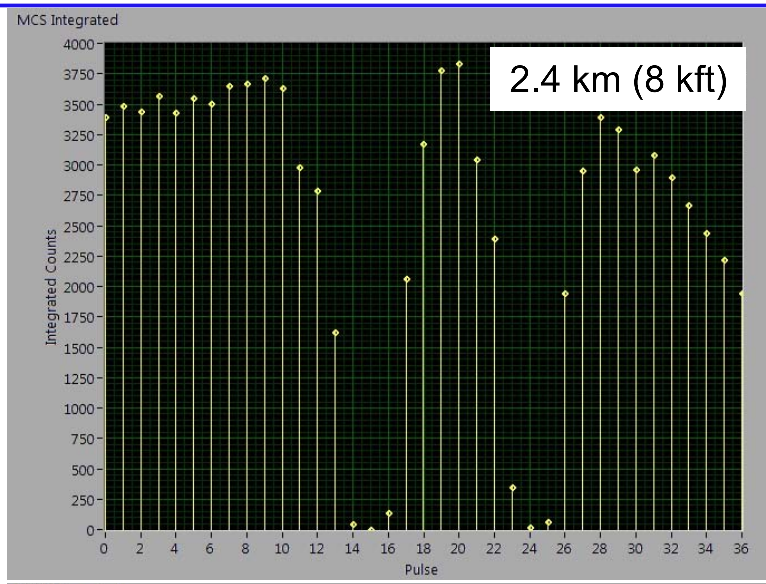

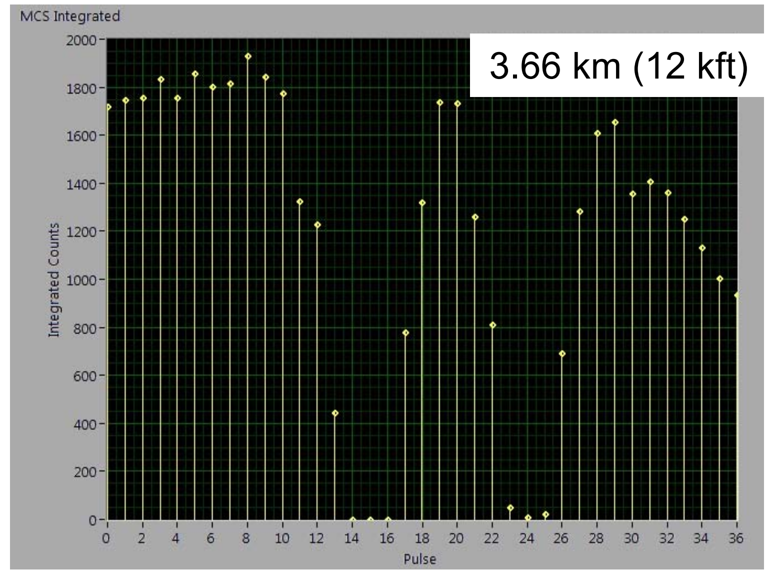

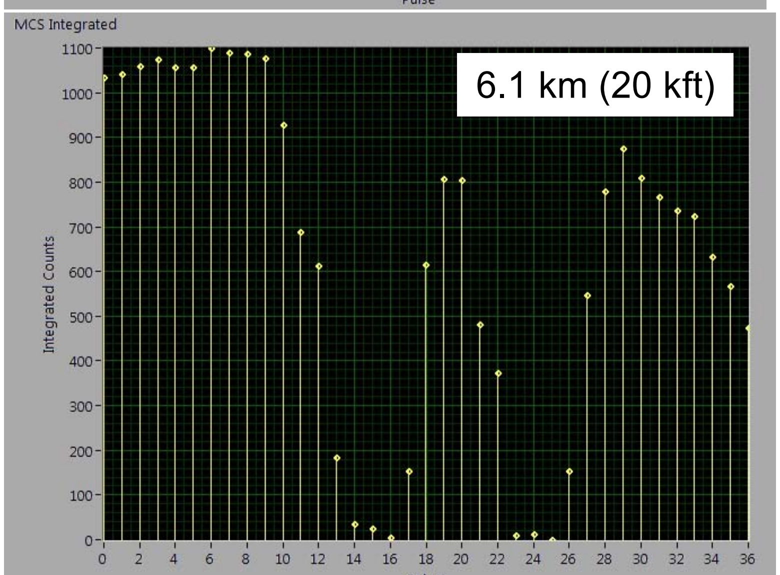

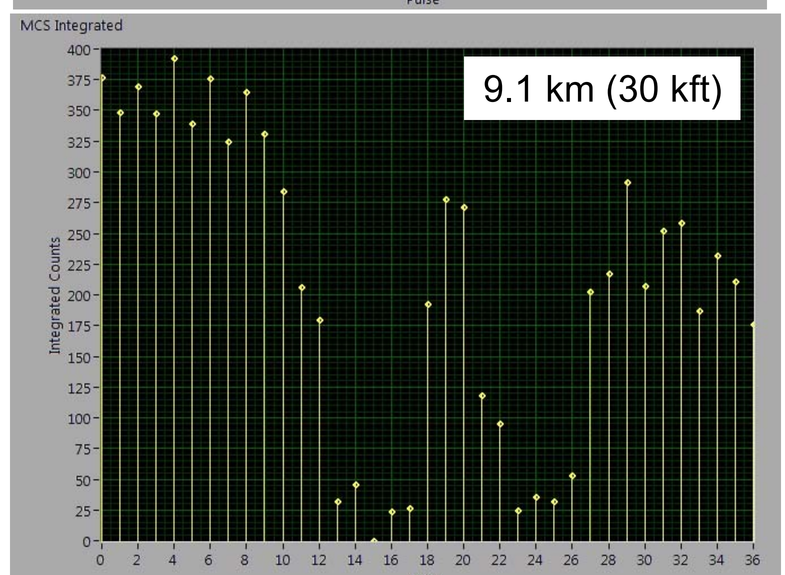

- **1st measurements, Initial look at data, Little processing, Not yet calibrated**
- Laser energy ~2 uJ/pulse, Ave laser power ~10 mW, 20 sec averaging

Summary of 2 Space Lidar Studies

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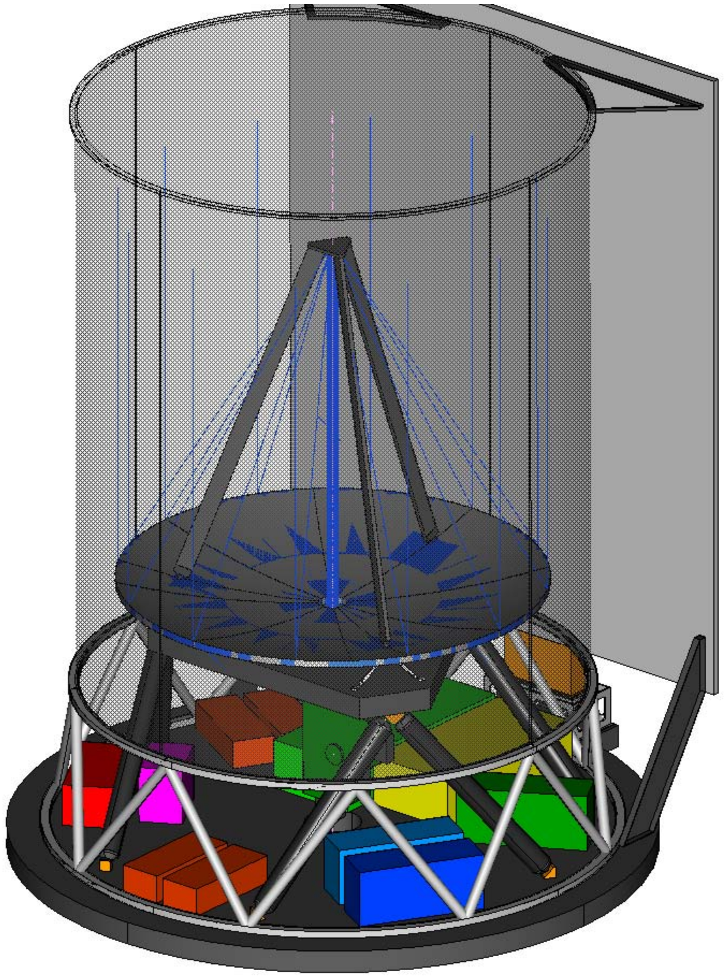
- Conducted studies of this approach for ASCENDS space lidar: 4/08 & 9/09
- Straightforward space lidar design:
  - Mass: ~ 400 Kg
  - Power: ~ 850W (with 3dB margin); driven by SNR needs
  - Data rate: ~1.9 Mbit/sec
- Low risk: Space qualified telescope, O2 detectors
- Detectors: reliability via multiple detectors & spares.
- Primary power draw: lasers
- Lasers: high efficiency & reliability
- Mission compatible with medium class rocket

(Taurus-II or equivalent), with considerable margin

- Can be further optimized in future studies



Layout concept from 1st study

Space: SNR & Relative Measurement Errors

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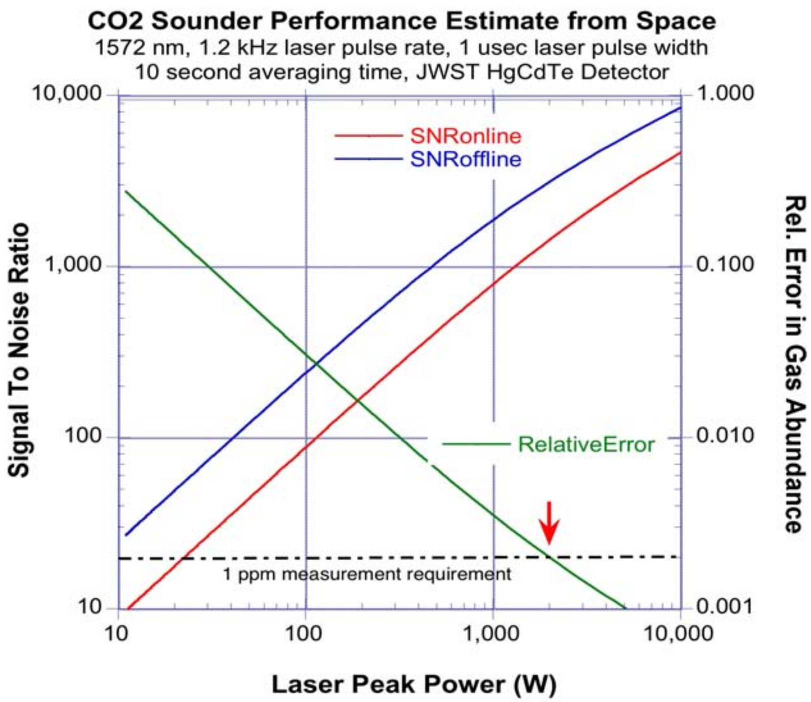
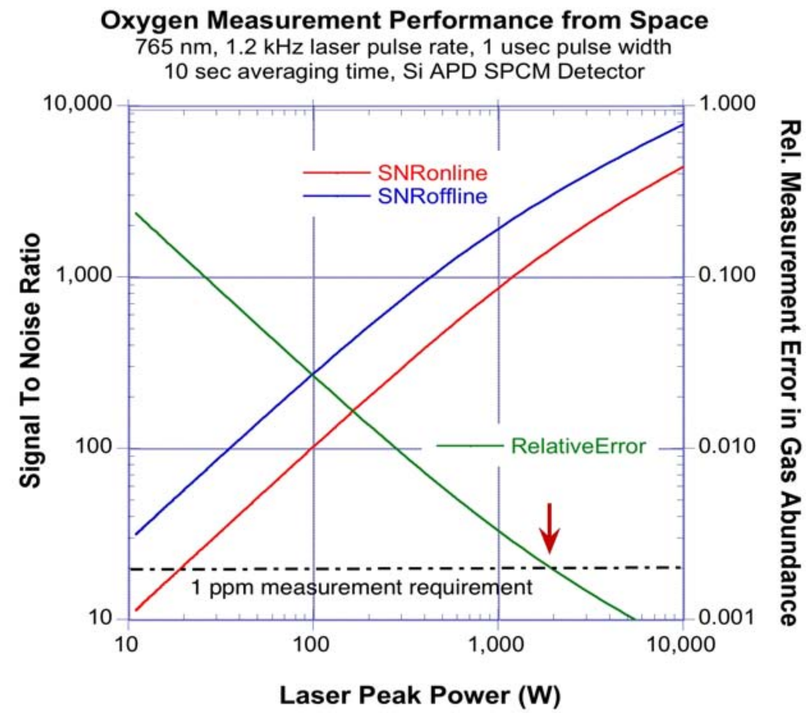
(10 seconds observing time, 500* km orbit, 1.5m telescope)

CO2 column measurement



O2 column measurement



~ 3 mJ/pulse energy (HgCdTe detector*)

~ 3 mJ/pulse energy (SPCM detector)

6 mJ energy from 1530 nm amp, 50% doubling

Ave optical power ~25-30W

Ave optical power ~25-30 W

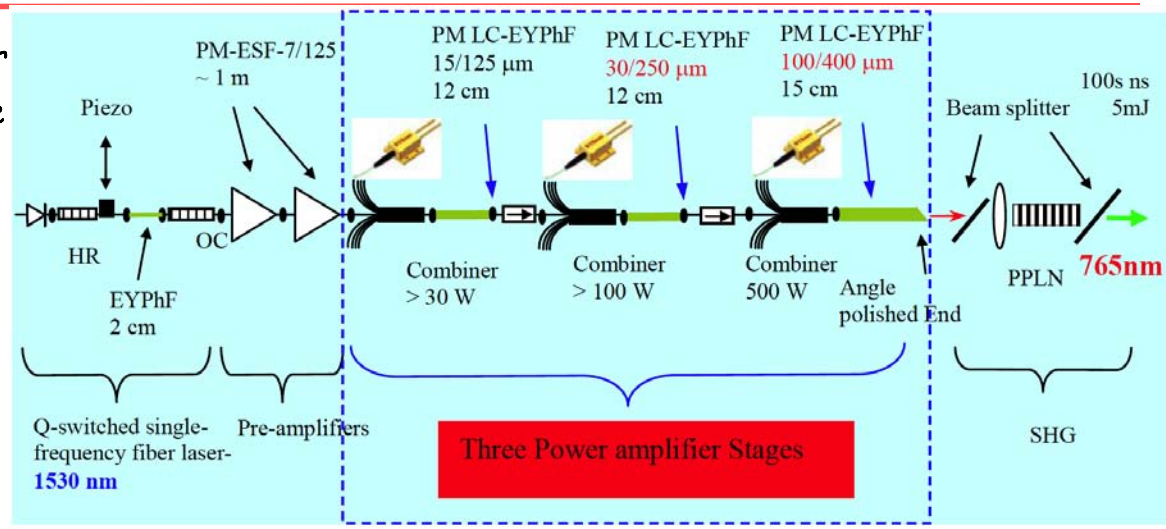
* - Same performance at 3 mJ/pulse with PMTs at 400 km orbit

Rel Measurement Errors scale as (laser pulse energy)$^{-1}$*(T)$^{-1/2}$

Laser Power Scaling to 3-6 mJ/pulse

1. High SBS-threshold Er/Yb co-doped phosphate glass fiber amplifier

- High SBS-threshold, SM, PM, high power amplifiers using NP Photonics large core SINGLE-MODE PM highly Er/Yb co-doped phosphate fibers
- Develop amplifier prototypes/products: 50μJ, 100s μJ and mJ.
- Push the SBS threshold to 100s kW.



SBIR (-1 & -2) with NP Photonics (Wei Shi,PI)

Near-term Raytheon applications of fiber lasers have been in various versions of laser sensors, including a state-of-the-art coherent laser radar system. In the commercial world, fiber lasers are becoming the laser of choice in a number of laser processing applications, most significantly in the marking area where they essentially dominate all other options.

Planar Waveguide Lasers (PWGs), are high aspect ratio sandwich-type structures consisting of a high-index active core surrounded by lower index claddings. A PWG is essentially a one-dimensional fiber in which the thin transverse axis is guided and the wide transverse axis is unguided. The core, typically 5 to 200 µm thick, may be single-mode or multimode and may be

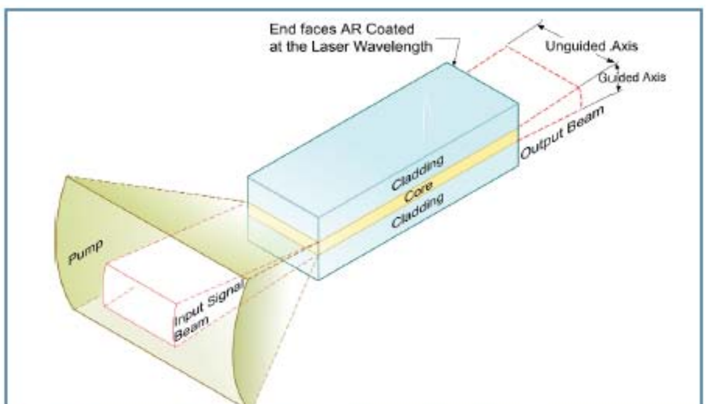


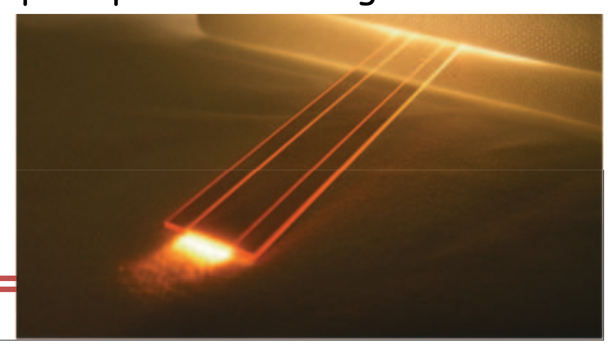
Figure 2. Planar waveguide gain medium showing pump insertion and output beam

Raytheon
Customer Success Is Our Mission

2. Amplifier R&D

Planar Waveguide Amplifiers

Planar waveguides allow guided mode amplification with much larger areas
=> higher peak powers & energies



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Summary

CO2 Sounder approach for ASCENDS:

- CO2 and O2 measurements:
  - Line shape & column heights
  - 2 altitude weighting functions
  - Pulsed lasers & multi–λ samples:

    Robust against instrument errors

    & atmospheric scattering
- Airborne column measurements:

  CO2 in 2008, 2009, 2010

  O2 (1st time) in 2010
- Laser components needed are practical
- 1st Mission simulations show meets science

  needs, more are being carried out
- ASCENDS launch scheduled for 2019

More Information (papers in *Tellus-B*) ->

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TELLUS

Simulation studies for a space-based CO_2 lidar mission

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ABSTRACT

We report results of initial space mission simulation studies for a laser-based, atmospheric CO_2 sounder, which are based on real-time carbon cycle process modelling and data analysis. The mission concept corresponds to the Active Sensing of CO_2 Emissions over Nights, Days and Seasons (ASCENDS) recommended by the US National Academy of Sciences' Decadal Survey. As a pre-requisite for meaningful quantitative evaluation, we employ a CO_2 model that has representative spatial and temporal gradients across a wide range of scales. In addition, a relatively complete description of the atmospheric and surface state is obtained from meteorological data assimilation and satellite measurements. We use radiative transfer calculations, an instrument model with representative errors and a simple retrieval approach to quantify errors in 'measured' CO_2 distributions, which are a function of mission and instrument design specifications along with the atmospheric/surface state. Uncertainty estimates based on the current instrument design point indicate that a CO_2 laser sounder can provide data consistent with ASCENDS requirements and will significantly enhance our ability to address carbon cycle science questions. Test of a dawn/dusk orbit deployment, however, shows that diurnal

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TELLUS

Pulsed airborne lidar measurements of atmospheric CO_2 column absorption

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ABSTRACT

We report initial measurements of atmospheric CO_2 column density using a pulsed airborne lidar operating at 1572 nm. It uses a lidar measurement technique being developed at NASA Goddard Space Flight Center as a candidate for the CO_2 measurement in the Active Sensing of CO_2 Emissions over Nights, Days and Seasons (ASCENDS) space mission. The pulsed multiple-wavelength lidar approach offers several new capabilities with respect to passive spectrometer and other lidar techniques for high-precision CO_2 column density measurements. We developed an airborne lidar using a fibre laser transmitter and photon counting detector, and conducted initial measurements of the CO_2 column absorption during flights over Oklahoma in December 2008. The results show clear CO_2 line shape and absorption signals. These follow the expected changes with aircraft altitude from 1.5 to 7.1 km, and are in good agreement with column number density estimates calculated from nearly coincident airborne in-situ measurements.